

Possible Quadrupole-first Options with $\beta^* \leq 0.25$ m and small angle *(preliminary)*

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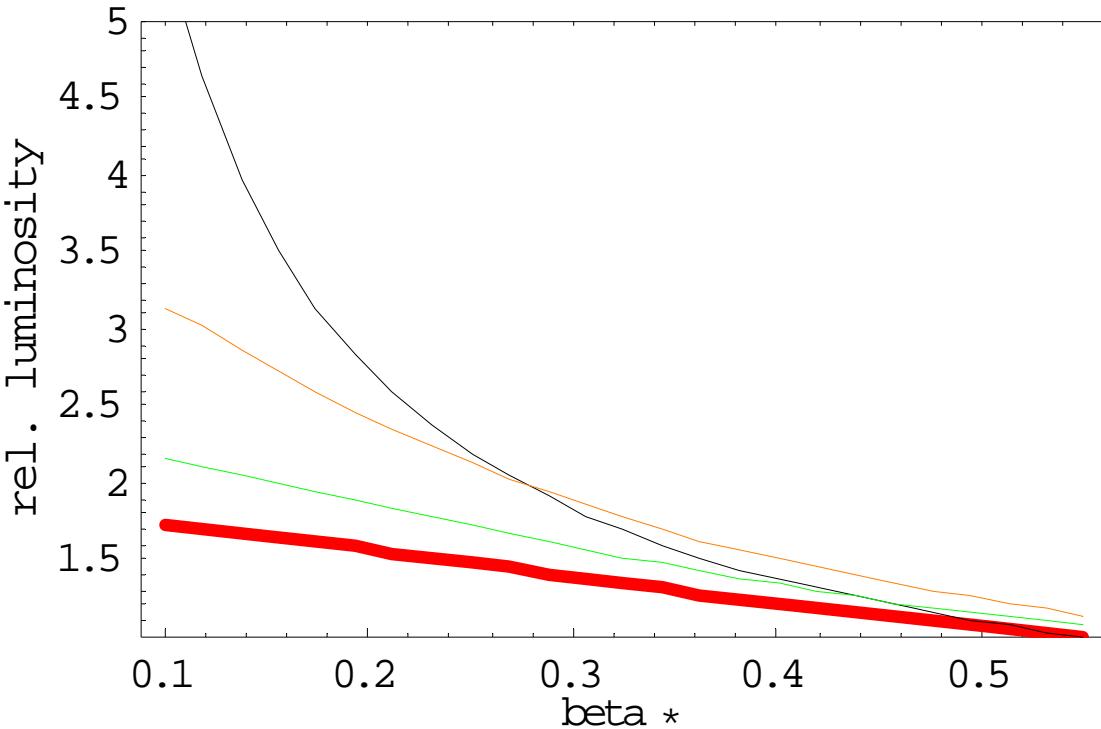
Outline

- 1. Overview of the anticipated advantages and drawbacks of the quad-first solution**
- 2. The yield from a reduced beta***
- 3. The internal wheels of the simplified scaling model used**
- 4. Comparison of a range of solutions**
- 5. An early separation scheme**
- 6. Preliminary conclusions**

General Advantages and Drawbacks

Advantages	Drawbacks
Minimization of β_{\max} , optical aberrations and sensitivity: most robust <i>optics solution</i> . Larger potential for beta* reduction	Strong coupling to other upgrade options thru Xing angle and aperture: goal must be well defined
The magnet most exposed to debris is as well the less sensitive (sweeps less)	Long-range beam-beam stronger → beam sep. increases by 20% (ultimate); larger Q aperture.
<i>Builds on the operational experience of 1rst generation: potential gain in $\int \mathcal{L} dt$</i>	<i>The two LHC rings remain coupled: operations more involved but large experience</i>

The yield from a reduced beta*



*Luminosity
increase vs
beta*:*

1. no Xing angle,
2. nominal Xing and bunch length,
3. BBLR?,
4. Bunch length/2

For both options and even more for the Q first, pushing the low-beta makes sense if simultaneously the impact of the Lumi. geometrical factor is acted upon.

A simple-minded exploration of the triplet parameter space

Goal: Investigate solutions based on a **scaled LHC triplet** vs

1. distance to the IP,
2. β^*
3. Beam intensity
4. Xing strategy and beam-beam compensation
5. Quadrupole length
6. Quadrupole technology
7. “oversize” factor for the inner coil diameter

Model output:

scenario

β_{IP} m	N_{bunch} 10^{11} p	k_b	X_{ing}	$\mathcal{L} / \mathcal{L}_0$
$\ell_{IP \rightarrow Q1}$ m	$< \ell_Q >$ m	ℓ_{LR} m	R12xCrab R12yCrab	
Gradient T/m	coil oversize	ϕ_{inner} coil mm	B_{max} T	power dens mW/g
Efficiency :	NbTi %	NbTiTa %	Nb3Sn %	
β_{max} m	K2[Q'] %	K2[Q', Q''] %	coef.b6	coef.b10
ϕ_{beam} mm	$\sigma_{\beta_{max}}$ mm	$a_{disp, max}$ mm	beam sep Q2 mm	θ_c μ rad

Discussion of the options (1)

Ingredients, scaling laws and recipes:

- **Xing strategy:** small angle: HV, HH, HH+BBLR
- **Triplet layout:** same as LHC with same relative quad. lengths.
LHC inter-quad space kept unscaled.
- **Gradient:** All triplet quads have the same gradient; scaled from nominal by
$$\frac{1}{l_{IP} + l_{triplet}/2}$$
followed by “*matching*” consisting in getting “reasonable” β ’s and α ’s at Q4 by small trims to the triplet the gradient.
- **$\langle lQ \rangle$:** average quad length.

Discussion of the options (2)

Ingredients, scaling laws and recipes:

- **Maximum beam extent**: β_{\max} , σ , a_{disp} , beam sep. are all taken in the middle of Q2 (thick lens transport), nominal ε .
- **Beam extent due to dispersion**: usual momentum range (0.86 E-3) in presence of spurious dispersion (0.4m in the arcs) *and the vertical dispersion excited by the HV Xing scheme.*
- **ℓ_{LR}** : Long-range interaction length: $\ell_{\text{IP}} + \ell_{\text{triplet}} + 2$

Discussion of the options (3)

Ingredients, scaling laws and recipes:

- Xing angle: BBLR suppresses intensity dependence

Papaphilippou-
Zimmerman
scaling

$$\theta_c \simeq \sqrt{\frac{\epsilon}{\beta^*}} \left(6.5 + 3 \sqrt{\frac{k_{par}}{2 \times 32} \frac{N_b}{10^{11}}} \right)$$

- Beam separation: effect of the Xing angle transported to the mid-Q2: *gives about 9.5 sigma.*

$$\overline{\phi_{beam}} = 1.1 \left(beamsep. + 2 \times 9 \sigma_\beta \right) + 2 \times \left(align = 1.6mm + co = 3mmm + a_{disp} \right)$$

Discussion of the options (4)

Ingredients, scaling laws and recipes:

- K2: Relative excitation of the lattice sextupoles scaled from version 4 (LHC PN38) + 20% inefficiency due to phase advance.

$$K2 = 26 + 18 + 2 \times 9 \frac{\beta_{\max} K_Q l_Q}{(\beta_{\max} K_Q l_Q)_0} \left\{ + 1.2 \times 2 \times 8.5 \left(\frac{\beta_{\max} K_Q l_Q}{(\beta_{\max} K_Q l_Q)_0} \right)^2 \right\}$$

- Geometric aberrations:

$$b6 \propto \beta_{\max}^3 K_Q l_Q$$

$$b10 \propto \beta_{\max}^5 K_Q l_Q$$

Discussion of the options (5)

Ingredients, scaling laws and recipes:

- **Innercoil diameter:**

$$\phi_{Icoil} = \phi_{beam} + 2 \times (\text{thickCB} = 1.8\text{mm}) + 2 \times (\text{thickBS} = 2.55\text{mm})$$

× coiloversize

- **Margins and efficiencies:**

- For NbTi and NbTiTa, ultimate performance is taken at 66% of critical field (13T, 14T), i.e. 8.6T and 9.2T.
- For Nb3Sn, this is taken to 57% of 23T, i.e. 13T.

The *margin for reliable operation in presence of beam induced heat load* come on top (15 to 20%?)

Discussion of the options (6)

Ingredients, scaling laws and recipes:

- Power deposition in the coil:

First attempt, based on few readings

$$power \propto \mathcal{L} \times l_Q \times (G \times \phi_{beam}) \times \frac{5\sigma_{beam} + \phi_{sep}}{\phi_{Icoil}}$$

Nominal taken to be 0.4 mW/g; 5 σ chosen to fit a doubling of the power deposition as calculated by N. Mokhov.

Nominal LHC

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case1: nominal LHC scenario

β_{IP} 0.55 m	N_{bunch} $1.15 \cdot 10^{11}$ p	k_b 2808	X_{ing} HV	$\mathcal{L}/\mathcal{L}_0$ 1.02
$\ell_{IP \rightarrow Q1}$ 23. m	$\langle \ell_Q \rangle$ 5.9 m	ℓ_{LR} 55. m	33. – 0.034 lc 46. – 0.3 lc	
Gradient 204. T / m	coil oversize 1.04	$\phi_{inner coil}$ 70. mm	B_{max} 7.13 T	power dens 0.387 mW/g
Margin :	NbTi 16.9 %	NbTiTa 22.8 %	Nb3Sn 45.6 %	
β_{max} 4401.8 m	K2[Q'] 62. %	K2[Q', Q''] 67.1 %	coef.b6 1.	coef.b10 1.
ϕ_{beam} 58.8 mm	$\sigma_{\beta_{max}}$ 1.49 mm	$a_{disp, max}$ 2.34 mm	beam sep Q2 14. mm	θ_c 285. μ rad

Epac2004 solution

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case9: similar to EPAC2004 solution: NbTi technology with enlarged aperture
 $l_{Q2}=7.4\text{m}$, $G=196\text{T/m}$, efficiency 93%, $\phi_{beam}=79.4\text{mm}$, coil diameter 85 mm

β_{IP}	N_{bunch}	k_b	X_{ing}	$\mathcal{L} / \mathcal{L}_0$
0.25 m	$1.15 \cdot 10^{11} \text{ p}$	2808	HV	1.52
$\ell_{IP \rightarrow Q1}$	$<\ell_Q>$	ℓ_{LR}	29. – 0.33 lc	
22. m	7. m	59. m	49. – 0.42 lc	
Gradient	coil oversize	$\phi_{inner \text{ coil}}$	B_{max}	power dens
176. T / m	1.	97.5 mm	8.57 T	0.997 mW / g
Margin :	NbTi 0.156 %	NbTiTa 7.29 %	Nb3Sn 34.7 %	
β_{max}	$K2[Q']$	$K2[Q', Q'']$	coef.b6	coef.b10
10508. m	87.7 %	118. %	13.84	78.86
ϕ_{beam}	$\sigma_{\beta_{max}}$	$a_{disp, max}$	beam sep Q2	θ_c
88.8 mm	2.3 mm	5.03 mm	21.9 mm	427. μrad

Pac2005 Cern solution

Case10: similar to CERN/PAC2005: NbTi technology with enlarged aperture

$l_Q = 8 \text{ m}$, $G = 150 \text{ T/m}$, $\beta_{\max} = 11.5 \text{ to } 11.8 \text{ km}$, efficiency 83%, coil diameter 95 mm

β_{IP}	N_{bunch}	k_b	X_{ing}	$\mathcal{L}/\mathcal{L}_0$
0.25 m	$1.15 \cdot 10^{11} \text{ p}$	2808	HV	1.51
$\ell_{IP \rightarrow Q1}$	$<\ell_Q>$	ℓ_{LR}	31. – 0.37 Ic	
23. m	8. m	64. m	53. – 0.43 Ic	
Gradient 143. T / m	coil oversize 1.	ϕ_{inner} coil 104. mm	B_{\max} 7.48 T	power dens 1.01 mW/g
Margin :	NbTi 12.8 %	NbTiTa 19. %	Nb3Sn 42.9 %	
β_{\max} 12182. m	K2[Q'] 91.2 %	K2[Q', Q''] 126. %	coef.b6 20.09	coef.b10 153.9
ϕ_{beam} 95.8 mm	$\sigma_{\beta_{\max}}$ 2.48 mm	$a_{\text{disp, max}}$ 5.66 mm	beam sep Q2 23.9 mm	θ_c 432. μ rad

Optimization at $l^=18m$*

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case13: the best I could find with Nb-Ti , moving the quads closer to the IP

β_{IP} 0.25 m	N_{bunch} $1.15 \cdot 10^{11} p$	k_b 2808	Xing HV	$\mathcal{L}/\mathcal{L}_0$ 1.53
$\ell_{IP \rightarrow Q1}$ 18. m	$<\ell_Q>$ 7.6 m	ℓ_{LR} 57. m	26. – 0.3 lc 51. – 0.39 lc	
Gradient 160. T / m	coil oversize 1.	$\phi_{inner coil}$ 89.8 mm	B_{max} 7.2 T	power dens 0.895 mW/g
Margin:	NbTi 16.1 %	NbTiTa 22.1 %	Nb3Sn 45.1 %	
β_{max} 8770.7 m	K2[Q'] 80.2 %	K2[Q', Q''] 101. %	coef.b6 7.977	coef.b10 31.67
ϕ_{beam} 81.1 mm	$\sigma_{\beta_{max}}$ 2.1 mm	$a_{disp, max}$ 4.21 mm	beam sep Q2 19.9 mm	θ_c 425. μ rad

Optimization at $l^=18m$ with ultimate beam current*

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case13b: the Nb-Ti solution with the ultimate current

β_{IP} 0.25 m	N_{bunch} $1.7 \cdot 10^{11} p$	k_b 5616	X_{ing} HV	$\mathcal{L}/\mathcal{L}_0$ 5.77
$\ell_{IP \rightarrow Q1}$ 18. m	$<\ell_Q>$ 7.6 m	ℓ_{LR} 57. m	26. – 0.3 Ic 51. – 0.39 Ic	
Gradient 160. T/m	coil oversize 1.	ϕ_{inner} coil 95.6 mm	B_{max} 7.67 T	power dens 3.91 mW/g
Margin :	NbTi 10.6 %	NbTiTa 17. %	Nb3Sn 41.5 %	
β_{max} 8770.7 m	K2[Q'] 80.2 %	K2[Q', Q''] 101. %	coef.b6 7.977	coef.b10 31.67
ϕ_{beam} 86.9 mm	$\sigma_{\beta_{max}}$ 2.1 mm	$a_{disp, max}$ 4.62 mm	beam sep Q2 24.5 mm	θ_c 522. μ rad

Nb3Sn: Optimization at $l^=23m$*

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case14-1: Nb3Sn triplet at 23m, otherwise nominal conditions

β_{IP} 0.25 m	N_{bunch} $1.15 \cdot 10^{11}$ p	k_b 2808	Xing HV	$\mathcal{L}/\mathcal{L}_0$ 1.54
$\ell_{IP \rightarrow Q1}$ 23. m	$< \ell_Q >$ 5.5 m	ℓ_{LR} 54. m	31. – 0.12 l _c 44. – 0.35 l _c	
Gradient 234. T / m	coil oversize 1.	ϕ_{inner} coil 92.4 mm	B _{max} 10.8 T	power dens 0.982 mW/g
Margin :	NbTi –26.3 %	NbTiTa –17.3 %	Nb3Sn 17.3 %	
β_{max} 9373.1 m	K2[Q'] 84.9 %	K2[Q', Q''] 111. %	coef.b6 10.3	coef.b10 46.7
ϕ_{beam} 83.7 mm	$\sigma_{\beta_{max}}$ 2.17 mm	a _{disp, max} 4.58 mm	beam sep Q2 20.4 mm	θ_c 421. μ rad

Nb3Sn: Optimization at $l^=23m$, high intensity*

case14-2: Nb3Sn triplet at 23m, ultimate beam current

β_{IP} 0.25 m	N_{bunch} $1.7 \cdot 10^{11}$ p	k_b 5616	X_{ing} HV	$\mathcal{L} / \mathcal{L}_0$ 5.79
$\ell_{IP \rightarrow Q1}$ 23. m	$< \ell_Q >$ 6. m	ℓ_{LR} 56. m	31. – 0.2 lc 46. – 0.37 lc	
Gradient 211. T / m	coil oversize 1.	ϕ_{inner} coil 101. mm	B_{max} 10.7 T	power dens 4.35 mW / g
Margin : –24.4 %	NbTi –15.5 %	NbTiTa 18.6 %		
β_{max} 9939.4 m	K2[Q'] 86.5 %	K2[Q', Q"] 115. %	coef.b6 12.04	coef.b10 61.41
ϕ_{beam} 92.6 mm	$\sigma_{\beta max}$ 2.24 mm	$a_{disp, max}$ 5.32 mm	beam sep Q2 25.9 mm	θ_c 519. μrad

Nb3Sn: Optimization at $l^=23m$, high intensity, BBLR*

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case14-3: Nb3Sn triplet at 23m, ultimate beam current, HH Xing with BBLR

β_{IP} 0.25 m	N_{bunch} $1.7 \cdot 10^{11} p$	k_b 5616	Xing BBLR	$\mathcal{L}/\mathcal{L}_0$ 6.7
$\ell_{IP \rightarrow Q1}$ 23. m	$<\ell_Q>$ 5.5 m	ℓ_{LR} 54. m	31. – 0.12 Ic 44. – 0.35 Ic	
Gradient 234. T/m	coil oversize 1.	$\phi_{inner coil}$ 88.4 mm	B_{max} 10.4 T	power dens 4.27 mW/g
Margin :	NbTi –20.7 %	NbTiTa –12.1 %	Nb3Sn 21. %	
β_{max} 9373.1 m	K2[Q'] 84.9 %	K2[Q', Q''] 111. %	coef.b6 10.3	coef.b10 46.7
ϕ_{beam} 79.7 mm	$\sigma_{\beta_{max}}$ 2.17 mm	$a_{disp, max}$ 2.48 mm	beam sep Q2 20.5 mm	θ_c 423. μ rad

case15-2bis: Nb3Sn triplet at 19m, ultimate beam current

β_{IP} 0.25 m	N_{bunch} $1.7 \cdot 10^{11} p$	k_b 5616	X_{ing} HV	$\mathcal{L}/\mathcal{L}_0$ 5.9
$\ell_{IP \rightarrow Q1}$ 19. m	$<\ell_Q>$ 5.5 m	ℓ_{LR} 50. m	27. – 0.16 lc 42. – 0.34 lc	
Gradient 248. T / m	coil oversize 1.02	ϕ_{inner} coil 90. mm	B_{max} 11.2 T	power dens 3.9 mW / g
Margin :	NbTi –30. %	NbTiTa –20.7 %	Nb3Sn 14.9 %	
β_{max} 7383.3 m	K2[Q'] 78. %	K2[Q', Q''] 96.3 %	coef.b6 5.322	coef.b10 14.97
ϕ_{beam} 79.4 mm	$\sigma_{\beta_{max}}$ 1.93 mm	$a_{disp, max}$ 4.07 mm	beam sep Q2 21.8 mm	θ_c 507. μ rad

case15-2ter: Nb3Sn triplet at 19m, ultimate beam current
with BBLR and take advantage to squeeze more

β_{IP} 0.19 m	N_{bunch} $1.7 \cdot 10^{11}$ p	k_b 5616	Xing BBLR	$\mathcal{L} / \mathcal{L}_0$ 7.23
$\ell_{IP \rightarrow Q1}$ 19. m	$< \ell_Q >$ 5.5 m	ℓ_{LR} 50. m	27. – 0.16 Ic 42. – 0.34 Ic	
Gradient 248. T/m	coil oversize 1.	$\phi_{inner coil}$ 89.6 mm	B_{max} 11.1 T	power dens 4.97 mW/g
Margin :	NbTi –29.5 %	NbTiTa –20.2 %	Nb3Sn 15.3 %	
β_{max} 9714.5 m	K2[Q'] 88.8 %	K2[Q', Q"] 120. %	coef.b6 12.12	coef.b10 59.04
ϕ_{beam} 80.9 mm	$\sigma_{\beta max}$ 2.21 mm	$a_{disp, max}$ 2.53 mm	beam sep Q2 20.8 mm	θ_c 485. μrad

case15-2quad: Nb3Sn triplet at 19m, ultimate beam current
 with BBLR and take advantage to squeeze more
 Bunch length reduced by 2

β_{IP} 0.19 m	N_{bunch} $1.7 \cdot 10^{11}$ p	k_b 5616	Xing BBLR	$\mathcal{L} / \mathcal{L}_0$ 11.2
$\ell_{IP \rightarrow Q1}$ 19. m	$< \ell_Q >$ 5.5 m	ℓ_{LR} 50. m	27. – 0.16 lc 42. – 0.34 lc	
Gradient 248. T / m	coil oversize 1.	$\phi_{inner coil}$ 89.6 mm	B_{max} 11.1 T	power dens 7.68 mW / g
Margin : Margin :	NbTi – 29.5 %	NbTiTa – 20.2 %	Nb3Sn 15.3 %	
β_{max} 9714.5 m	K2[Q'] 88.8 %	K2[Q', Q''] 120. %	coef.b6 12.12	coef.b10 59.04
ϕ_{beam} 80.9 mm	$\sigma_{\beta_{max}}$ 2.21 mm	$a_{disp, max}$ 2.53 mm	beam sep Q2 20.8 mm	θ_c 485. μrad

case16-2: Nb3Sn triplet at 16m, ultimate current, BBLR, super-squeeze

β_{IP} 0.18m	N_{bunch} $1.7 \cdot 10^{11}$ p	k_b 5616	Xing BBLR	$\mathcal{L}/\mathcal{L}_0$ 7.32
$\ell_{IP \rightarrow Q1}$ 16. m	$<\ell_Q>$ 5.5m	ℓ_{LR} 47. m	24. – 0.17lc 41. – 0.32lc	
Gradient 258. T/m	coil oversize 1	$\phi_{inner coil}$ 84.4mm	B_{max} 10.9T	power dens 4.83 mW/g

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Margin:	NbTi –27.1%	NbTiTa –18. %	Nb3Sn 16.8%	case16-2: Nb3Sn triplet at 16m, ultimate current, BBLR, super-squeeze bunch length divided by 2
β_{max} 8346.5m	K2[Q'] 84.1%	K2[Q', Q''] 109. %	coef.b6 8.015	coef.b' 28.82
ϕ_{beam} 75.7mm	$\sigma_{\beta_{max}}$ 205mm	$a_{disp, max}$ 234mm	beamsepQ2 19.3mm	θ_c 498. μ rad
β_{IP} 0.18m	N_{bunch} $1.7 \cdot 10^{11}$ p	k_b 5616	Xing BBLR	$\mathcal{L}/\mathcal{L}_0$ 11.5
$\ell_{IP \rightarrow Q1}$ 16. m	$<\ell_Q>$ 5.5m	ℓ_{LR} 47. m	24. – 0.17lc 41. – 0.32lc	
Gradient 258. T/m	coil oversize 1	$\phi_{inner coil}$ 84.4mm	B_{max} 10.9T	power dens 7.59 mW/g
Margin:	NbTi –27.1%	NbTiTa –18. %	Nb3Sn 16.8%	
β_{max} 8346.5m	K2[Q'] 84.1%	K2[Q', Q''] 109. %	coef.b6 8.015	coef.b10 28.82
ϕ_{beam} 75.7mm	$\sigma_{\beta_{max}}$ 205mm	$a_{disp, max}$ 234mm	beamsepQ2 19.3mm	θ_c 498. μ rad

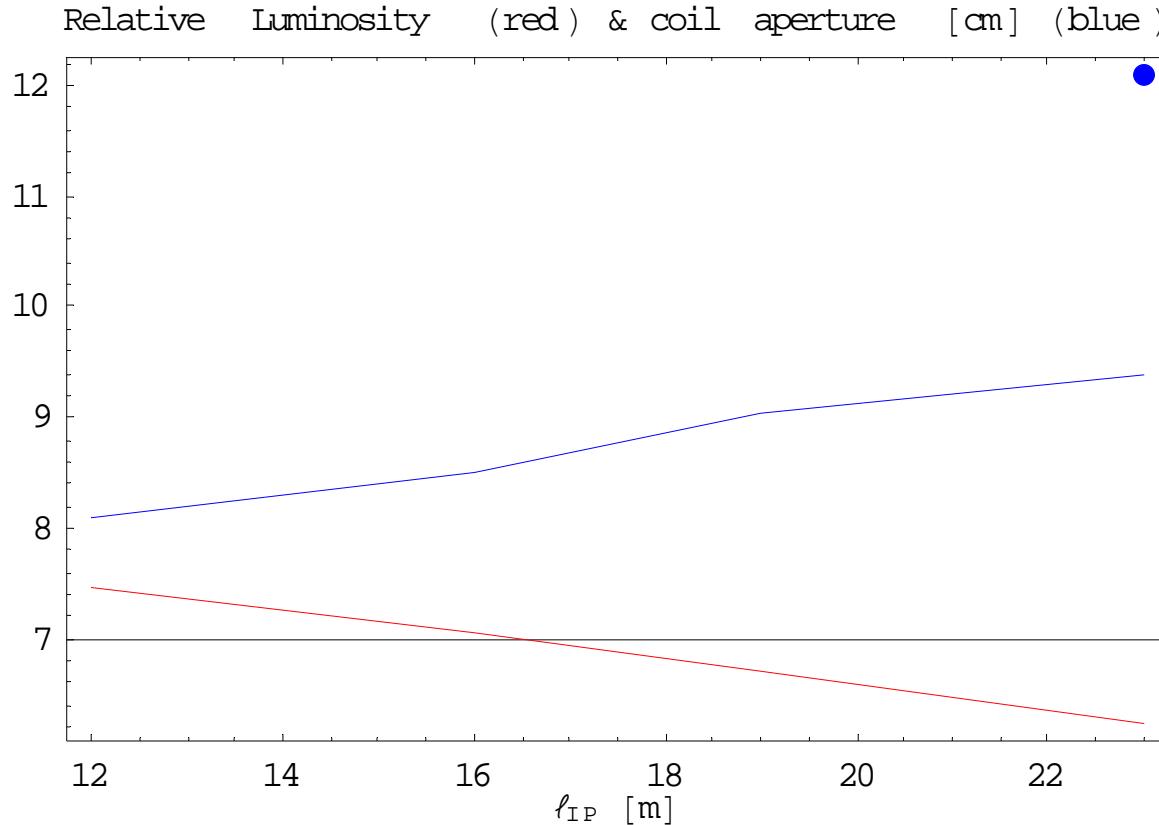
case17-3: Nb3Sn triplet at 12m, ultimate beam current, HH Xing with BBLR
super-squeeze

β_{IP} 0.15 m	N_{bunch} $1.7 \cdot 10^{11}$ p	k_b 5616	Xing BBLR	$\mathcal{L} / \mathcal{L}_0$ 7.56
$\ell_{IP \rightarrow Q1}$ 12. m	$<\ell_Q>$ 5.5 m	ℓ_{LR} 43. m	19. – 0.19 lc 40. – 0.33 lc	
Gradient 277. T/m	coil oversize 1.	$\phi_{inner coil}$ 80. mm	B_{max} 11.1 T	power dens 4.96 mW/g
Margin :	NbTi –29.1 %	NbTiTa –19.9 %	Nb3Sn 15.5 %	
β_{max} 7287.1 m	K2[Q'] 81.5 %	K2[Q', Q''] 104. %	coef.b6 5.712	case17-3: Nb3Sn triplet at 12m, ultimate beam current, HH Xing with BBLR super-squeeze and bunch length halved
ϕ_{beam} 71.3 mm	$\sigma_{\beta_{max}}$ 1.91 mm	$a_{disp, max}$ 2.19 mm	beam sep Q2 18. mm	

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β_{IP} 0.15 m	N_{bunch} $1.7 \cdot 10^{11}$ p	k_b 5616	Xing BBLR	$\mathcal{L} / \mathcal{L}_0$ 12.5
$\ell_{IP \rightarrow Q1}$ 12. m	$<\ell_Q>$ 5.5 m	ℓ_{LR} 43. m	19. – 0.19 lc 40. – 0.33 lc	
Gradient 277. T/m	coil oversize 1.	$\phi_{inner coil}$ 80. mm	B_{max} 11.1 T	power dens 8.21 mW/g
Margin :	NbTi –29.1 %	NbTiTa –19.9 %	Nb3Sn 15.5 %	
β_{max} 7287.1 m	K2[Q'] 81.5 %	K2[Q', Q''] 104. %	coef.b6 5.712	coef.b10 15.66
ϕ_{beam} 71.3 mm	$\sigma_{\beta_{max}}$ 1.91 mm	$a_{disp, max}$ 2.19 mm	beam sep Q2 18. mm	θ_c 546. μ rad

Partial conclusion on an upgrade using Nb3Sn technology



Early Separation Scheme (D0)

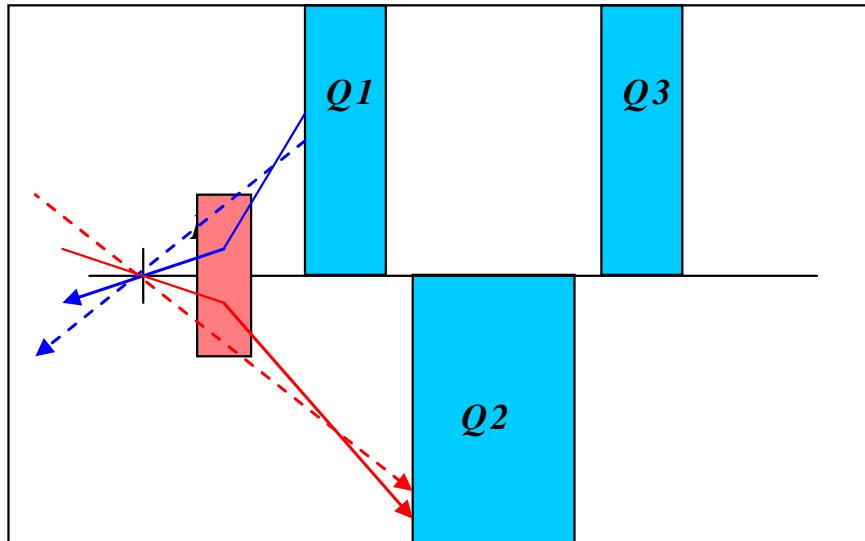


Figure 1: Principle of the early separation

An “easy” way to reduce or cancel the Xing angle at the IP and gain 20% to 50% in luminosity.

Ideally 1m away from IP, few meters still OK, 3 to 6 Tm needed.

Is it possible for the detectors?

Being followed up...

Conclusions (quad first, small angle)

1. The scaling of the beam separation and of the heat deposition are two critical issues for the definition of the triplet quadrupoles→checks welcome.
2. The Nb-Ti-Ta solutions have very limited scope and have potential chromatic problems. The Q aperture shall be at least 100 mm.
3. At 23m, the Nb₃Sn solutions require a quad aperture larger than 100 mm and suffer from the same chromatic problems. The BBLR reduces the demand to 90mm but no guaranty today.
4. At 19 m from IP, a 90 mm quad is OK with good luminosity and potential for significant improvements with BBLR and D0 or shorter bunches.
5. At 12m and 16m, the performance and potential are somewhat improving and the chromaticity issue totally disappears.
6. An early separation scheme (D0) is under evaluation.
7. The possibility of moving the triplet towards/in the detectors will be investigated